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Evaluation of Designer Feedback Systems in Design for Manufacturability

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***Abstract* – The research study introduces a new designer feedback tool called Three Dimensional Integrated Feedback (3DIF) tool to convey manufacturability analysis results early in the conceptual design phase. The study evaluates and compares different modalities of manufacturability feedback given to design engineers. The conceptual design stage is critical in determining the feasibility of the whole production process. Providing designers with early suggestions and feedback about the manufacturability of product designs will help to improve their design and save time and cost to manufacture. Feedback given to the design engineers could be in any form text, 2D markups, 3D data or verbal. Feedback can contain insufficient data or can be difficult to interpret leading to frequent design iterations and increase in lead time. It is important that feedback should be able to convey necessary design information and should be in language understandable by design engineers. The modality of feedback affects interpretability of the data presented. The study compares between no feedback, text-based feedback, 2D feedback and 3D feedback modalities in the casting process of manufacturing. The results expected from the study will help us to determine the appropriate modality of feedback that improves design performance of both expert and novice designers.**

I. INTRODUCTION

The manufacturability of a design determines 80% percent of the production cost [1]. Fig 1 shows a cost-influence curve in accordance with Paulson's curve [2].

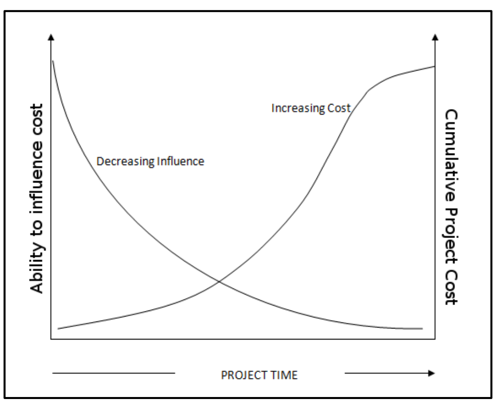

Fig 1- Cost influence curve based on Paulson's curve [2]

Although the actual expenditures during early phases of a project are comparatively small, decisions and commitments made during that period have orders of magnitude greater influence on what the total expenditures will actually be [3] [4]. Good design makes products more competitive, better, cheaper and quicker to manufacture. It keeps the production costs down [5]. So, it is mandatory that all the critical design decisions are made during the conceptual design stage. Typically, design and manufacturing engineers have different roles and they work independent of each other, often separated across distant geographical locations. In a process that is termed "throwing-it-over-the-wall", design engineers focus on brainstorming ideas and creating designs that meet all the expected functional requirements; manufacturing engineers, on the other hand, focus on processes and cost to convert the proposed design into a manufactured product. The designs created by the designers often meet the functional requirements but fail to meet the manufacturability constraints usually because designers lack thorough manufacturing knowledge [6]. This makes a design process iterative where features difficult or expensive to manufacture are redesigned by the design engineers based on feedback given by the manufacturing unit. These iterative loops between design and manufacturing teams make the whole new product development linger at the design stage [7]. It has been reported that the design process can usually take up to 24 months in North America [8] and 15 to 20 years [9] for military vehicles particularly from the concept initiation to the production phase.

Design for Manufacturing (DFM) bridges the gap between conceptual design and manufacturing by bringing manufacturing knowledge early in the design process. To avoid lengthy feedback cycle time, automated DFM tools are used. These software tools analyse designs against manufacturability guidelines and provide design engineers with analysis results or redesign suggestions [10]. The feedback given to the design engineers should not only contain all the necessary manufacturability analysis information but also be easily interpretable and usable by them because design engineers lack intensive manufacturing knowledge.

Evaluating different modalities of feedback will help to identify suitable mode(s) of feedback that can facilitate design performance. The modality of feedback plays crucial role in determining interpretability of the data, for example, a triangular plane is better represented in 2D drawings as compared to giving coordinate information of its three vertices in text, although both text and 2D contain the same amount of information, text seems abstract compared to 2D. Feedback that is both informative and intuitive to understand will significantly reduce the design loops and save time.

The study introduces a new tool called 3DIF tool which is expected to facilitate interpretability of manufacturing analysis information given to the conceptual designers at early stages of design process. The study will evaluate and compare the modality of 3DIF against some of the other modalities of feedback which exist like text-based feedback, 2D feedback. The study will observe design engineers using feedback in their actual work settings. This will help us to better understand the feasibility and in-context usefulness.

II. RELATED WORK

Commonly, Design for Manufacturability is accomplished through iterative spiral design process in which marketing experts, manufacturing experts, design engineers and other personnel jump back and forth between identification of customer needs, design of products and assessment of manufacturing issues [10]. As companies follow distributed manufacturing paradigm [12], marketing, design, and manufacturing departments have evolved into separate organizations, each with their own specialized knowledge. It is difficult to have frequent collaboration between groups of engineers. The division of teams hinders in knowledge flow and creates language barrier between the teams [13]. In order to help designers assess the manufacturability impacts of their designs, industries and researchers have developed Design for Manufacturability or DFM principles or guidelines.

There are previous work done to understand communication between designers and engineers in manufacturing industries. A research study [11] compared between individual and group design review process, it studied the effectiveness of different modalities of verbal communication methods like face to face, text only and speech only communication during design review process. The results showed that group reviews were approximately twice as effective as individual reviews. Although there wasn't any significant statistical difference between the measured effectiveness of design reviews under different communication modalities, the participants reported perceived effectiveness of face-to-face communication being more effective than speech only and speech only being more effective than the text only.

One of the other ways to accomplish DFM is with the help of manufacturability analysis software systems. These systems vary in approach, scope and level of sophistication [10]. Several automated DFM tools have been developed in the past. Anjanappa et al. [11] developed rapid prototyping tool for machined parts. The system lists features which are non-manufacturable or potentially difficult to manufacture. Cutkosky and Tenenbaum [12] developed NEXT-Cut. The system uses its knowledge-base to analyse design's manufacturability. Design engineers are warned, if any of the manufacturability constrained are violated. Work done by Huh and Kim [13] describes system for supporting concurrent design for injection molding. Both function and manufacturability are considered when providing help with design decisions. Feedback is provided in two forms: first, a quantitative measure of the probability of having different types of manufacturing defects like sink, marks, ejection difficulty. Second type of feedback is warning messages that indicate possible design issues.

Current state-of-the-art Intelligent CAD systems and advanced DFM tools like DFMPro [14], DFM concurrent costing by Boothroyd Dewhurst [15], Simulation DFM by Autodesk [16], Cast-Designer [17] can perform complex manufacturability analysis for multiple manufacturing processes. These tools give design engineers feedback to improve on their designs. Feedback given to the design engineers can be in the form of interactive simulation, coloured 3D format, 2D, or text. For example, DFMPro integrates with design CAD tools and provides 3D coloured feedback about the design. It further generates design reports in 2D and text. Boothroyd Dewhurst DFM tool provides detailed product manufacturability time and cost information in tabular format or 2D charts. Many manufacturing companies have their own set of manufacturing guidelines and develop DFM tools tailored according to their needs. General Electric was one of the pioneers to develop their own set of guidelines [18].

In manufacturing research there are novel manufacturability analysis tools developed which are capable of performing complex analysis. Two of the many tools that are developed and used under DARPA's (Defense Advanced Research Projects Agency) AVM's (Adaptive Vehicle Make) iFAB (instant Foundry, Adaptive through Bits) project are CNC-ANA (unpublished research) for machining analysis and CAST-ANA (unpublished research) for casting analysis. These tools performed multiple types of analysis for a particular type of manufacturing process and provided designers with detailed feedback about their design in the form of 3DIF.

For manufacturability analysis tools to be effective, they must provide some kind of manufacturability rating of the design. Systems can either provide detailed rating of design features [19] or can provide redesign suggestions [20]. Feedback which are usable, informative and in a language understandable by the design engineers can aid them to improve the quality of their designs with lesser design iterations. Interpretability of the data is significantly determined by the modality in which it is presented in.

A Study [21] shows that the format of material aids in self explanation and helps to develop deeper understanding of the material. The study was performed with text-based and figure-based learning materials and showed participants were able to learn more when provided with figures than with text only.

Several studies have been done in the field of, engineering design [22] [23], user interfaces [24], medical data visualization [25] that compares between the effect of visualization of 2-dimensional and 3-dimensional data.

As is often the case in engineering drawing, 3D objects are represented as 2D drawings. A study [26] evaluated cognitive process of mental imaging of 2D and 3D figures. It compares the accuracy and reaction time between four types of tasks: simple 2D, selective 2D, 2D-3D and 3D tasks. Reaction time for 2D-3D was significantly higher than the other cases. Accuracy for 2D-3D and selective 2D was significantly lower than the simple 2D or 3D case because they required higher working memory.

The previous study uses simple diagrams and models to measure accuracy and reaction time. Since, engineering drawings are generally complex, a study [27] compares the reaction time and accuracy between mentally creating 3D models from visualizing 2D engineering drawings and visualizing stereoscopic 3D of the same model. 3D visualization was only a little better than 2D in terms of accuracy and reaction time. The study concluded that the reaction time and accuracy for both the cases were quite similar and introduced a new type of engineering drawing approach called the Augmented Reality Technical drawing.

Case studies of visualization tools in realistic settings are the least common type of studies performed [28]. The authors found shortage of reported work on case studies evaluating the impact of designer feedback systems on design performance and workload of design engineers. This study described in this paper will observe design engineers using the 3DIF tool to conduct tasks in their usual work setting. This study will focus on finding the impact of different feedback modalities on designer performance and their cognitive workload.

The next section gives an overview of the 3DIF tool. Section IV described the study method. Section V briefly discusses the benefits and expected results of the study.

III. 3D INTEGRATED FEEDBACK TOOL (3DIF)

A 3DIF tool is a pdf document with multiple manufacturability analyses results represented in 3D and integrated within a single document. Fig 2 shows a 3DIF as generated by the castability analysis tool, CAST -ANA. The 3DIF tool shows four windows each showing specific type of manufacturability analysis result. Each window shows the 3D colored feedback and a metadata region that primarily shows color legend and gives additional text based information. The four types of analysis results shown are Constant Cross Section Analysis (Top-Left), Isolated Heavy Section Analysis (Top-Right), Visibility from Primary Axis (Bottom-Left) and Core area Analysis (Bottom-Right). The model is colored yellow by default.

The 3DIF can be integrated with most automated manufacturability analysis tools. Feedback can be represented as colored regions in the 3D models showing the region of interest. Geometric primitives like spheres, cones can be added to give other types of information like showing angles, hotspots. Since, the feedback data is embedded in a pdf, it is highly portable and easy to distribute, thereby, making it easy to share information among different teams.

The following sections will give detailed information about the feedback windows shown in Fig 2.

A. Constant Cross Section (CCS) Analysis

Constant cross section analysis window is shown in Fig 3. The CCS regions are highlighted as flat red solid surfaces. CCS are regions of a part that have uniform thickness. In order to make a part more castable by promoting directional solidification it is important that those surfaces are slightly tapered. The design engineers can easily learn, from the feedback, about the CCS regions in their design and make the necessary changes to the design.

Fig 2 - 3DIF visual feedback, showing all four windows (CastingAna)

Fig 3 - constant cross section analysis window (CastingAna)

B. Isolated Heavy Section (IHS) Analysis

The analysis window (Fig 4) represents IHSs as red spheres. They are regions of larger volume and need risers. The sphere location determines the riser location and the size is approximately proportional to the volume of the riser needed to feed the IHS. The metadata region shows the number of IHS. Risers increase the cost of casting and their number needs to be minimized. The design engineers can learn about the risers needed for their part and redesign to reduce the number of IHSs. Or if they choose, complete the design as is, but risk cost and time penalties.

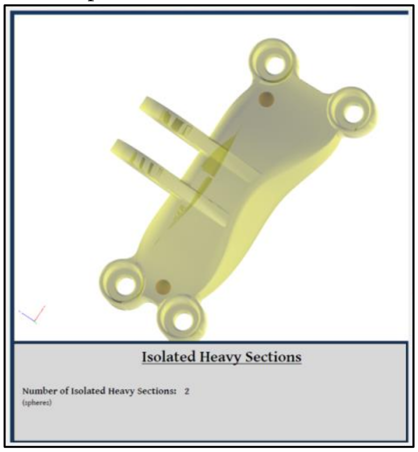

Fig 4 - isolated heavy section analysis window (CastingAna)

C. Visibility of Casting Surface (VCS) from Primary Axis

Visibility analysis window is shown in Fig 5. The regions that are not visible from 0 and 180 degrees about all the three primary axes, X, Y and Z are coloured red. The cones coloured as green, yellow and red represent the decreasing values of visibility percentages as calculated from angles 0 and 180 degrees about the three axes. The metadata information shows percentage visibility and the corresponding axis about which the visibility is found. The designers can learn about the non-visible regions and redesign the part to maximize visibility.

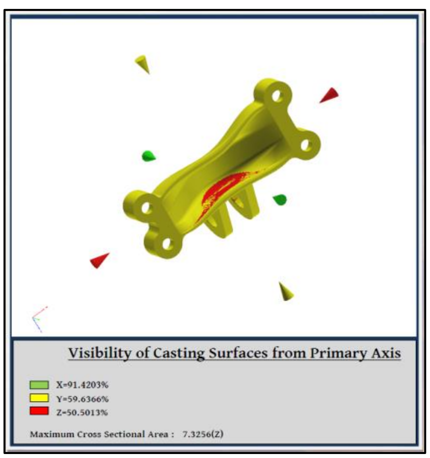

Fig 5 - visibility analysis (CastingAna)

D. Features that will likely require cores

The core analysis window (Fig 6) represents core regions as solid marching squares. The core regions corresponding to parting directions X, Y and Z are coloured as red, green and blue. For clarity, Fig 6 shows cores only for the Y-axis parting direction. Three checkboxes turn on and off cores corresponding to a particular parting direction. The core count and complexity may increase the cost of casting and hence needs to be minimized. The design engineers can learn about the regions in their part that will require core and redesign to reduce their count and/or complexity.

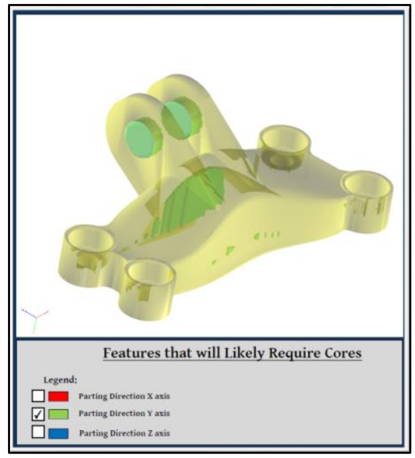

Fig 6 - core area analysis window (CastingAna)

IV. PROPOSED METHOD

A. Research Objective and Hypothesis

The aim of this work is to understand how different feedback modalities affect the design performance and cognitive workload of expert and novice designers of parts manufactured by the casting process. Providing feedback to the designers in any modality will help them to design faster and with less number of design flaws as compared to no feedback. A three dimensional visual feedback will help designers to design faster compared to two dimensional or text-based feedback.

B. Participants

Participants will be students or professionals. Student participants will have taken casting courses. Professional participants will have at least three months of professional casting design experience.

C. Independent Variables

There are two independent variables that we will control for our study: *Modality of feedback* (No feedback, Text feedback, 2D feedback and 3D PDF visual feedback) and *Designer Expertise level* (Expert, Novice).

D. Dependent Variables

The study will measure performance, workload, and usability:

- Number of expensive or bad casting-design features eliminated or reduced
- Time taken to redesign
- Cognitive workload based on NASA-TLX
- Comprehensibility rating of feedback

E. Experimental Design

The experiment follows a 2 (expertise) x 4 (modality) mixed design. Expertise is a between-subject variable whereas modality is a within-subject variable. Participants will conduct the design task in the following four scenarios:

- Redesigning part model with no feedback (NF).
- Redesigning part model with text feedback (TF).
- Redesigning part model with 2D feedback (2F).
- Redesigning part model with 3D feedback (3F).

Four different parts of equal difficulty will be randomly assigned to scenarios for each participant. Scenario order will be counterbalanced to mitigate any learning effects.

F. Tasks/ Scenarios

In the study the participants will conduct two types of tasks. They will fill out questionnaires at different stages of the study and conduct multiple trials of design task.

Participants will be provided with a consent form. The consent form has information related to risks, benefits, and participant's role in the study. Only after a participant has agreed with the consent form he or she will be allowed to participate in the rest of the study.

The participants will fill out a preliminary questionnaire. The questionnaire is related to participant's demographics, work and casting design experience. Based on the questionnaire, the participants will be grouped into two categories experts and novice.

The participants will be trained on the set of allowed CAD features, NASA-TLX survey and feedback tools used while conducting the actual design tasks. Participants will also conduct a sample design task with a sample model and all the type feedback to better understand the actual design task and reduce the training effect on the data.

During the actual design trials the participants will think-aloud, i.e. talk out loud about their though process and strategy to perform the task. They will be recorded while they conduct the task. The participants will be randomly assigned to one of the four scenarios. For every trial the participants will get different CAD models, each of similar level of complexity, and other documents containing design specification and constraints to follow when redesigning the model. They will be provided with one of the types of feedback and will have to interpret this feedback. Based on their feedback interpretation, the participants will have to redesign the original model with the goal of improving the design, i.e. redesign original model to reduce or eliminate the expensive or undesirable features. The participants will perform trials in all the four scenarios. Each trial will be followed by a post–trial questionnaire. The post-trial questionnaire is related to the participant's cognitive workload and performance during the trial.

After all the trials of the design task, the participants will be asked to fill out a post-experimental questionnaire. The post experimental questionnaire is related to comparisons between all the modalities of feedback used in the study. The participants also debrief about the 3D PDF visual feedback system.

G. Procedure

At the beginning of the study, Participants will be given a consent form to read and approve. Next they will fill out preliminary questionnaire. Next they undergo a training session to learn about the details of the experiment. They conduct all the four trials of the design task under different conditions and fill out the post trial questionnaire and workload survey after the end of each trial. They finally end with a post-experimental survey and debriefing about the 3D PDF visual feedback tool.

V. DISCUSSION

The expected study results will show how feedback modality affects design performance of expert and novice designers in casting. We are interested in measuring the improvement in design performance, in terms of time taken and number of flaws eliminated, and cognitive workload of designers.

Design performance is expected to be higher in 3D visual feedback mode compared to the other modes for both expert and novice designers. The experts are expected to perform better than novices in every feedback mode; however, this difference is expected to reduce when feedback is given in 3D.

Workload is expected to be lower when designing with 3D feedback. The workload of novice designers is expected to be greater than the expert designer in every mode, however, the difference between the workloads of novice and expert is expected to decrease in 3D feedback mode.

The results obtained from the experimental study will aid in further development of highly efficient designer feedback tools. The 3D PDF feedback tool is expected to be beneficial in manufacturing industries, large and small scaled, and research areas related to manufacturing. 3D PDF visual feedback could serve as a cheap and effective tool for communicating design information between various groups in manufacturing. It could enable manufacturers to adopt a complete 3D model based workflow. The tool of this nature is expected to facilitate early feedback in the design process which will streamline the design process and optimize other downstream manufacturing processes. The study will help us to understand the key differences between expert and novice designers. This will help us to refine the quality of the tool further that can assist both the types of designers.

VI. CONCLUSION

The research study is aimed at understanding the impact of different modalities of manufacturing feedback on design performance and cognitive workload of both expert and novice conceptual designers. Although the study will consider designers in casting process of manufacturing, the results are expected to generalize to other manufacturing processes. In addition, the user study will provide data to further improve the 3DIF visual feedback tool. Future work will involve testing the visualization tool in multiple manufacturing domains and test for the reduction in number of iterations as a direct measure of design performance.

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